Optimization of three-dimensional reinforced concrete shear-wall structures

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This report highlights an optimisation method considering a minimum cost of 3D Reinforced Concrete (RC) Shear Wall Structures.

I. JUSTIFICATION OF THE CHOICE:

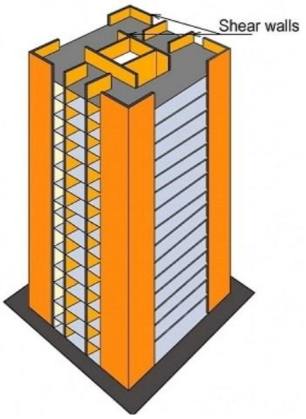
Population in the world is currently growing at a rate of around 1.05% per year. Yet, the available surface on the earth is unchanging. Many countries feel the need to solve the density problem and the lack of the current land for development. So, they adopted high-rise buildings as a solution. Tall building provides the opportunity to control urban sprawl. Others use these kind of structures as an indication to power and prestige status. However, during every earthquake, several aesthetic buildings suffered from severe structural damages. **Here it comes the importance of a structure that will increase the rigidity to lateral load and even the vertical resistance named Shear Wall Structures.**

II. INTRODUCTION:

1. General Information:

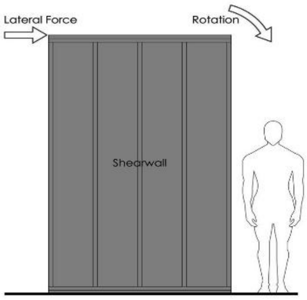
A Shear Wall is a structural member composed of braced panel to encounter the effects of lateral forces acting on a structure. Wind and seismic loads are the most common loads that shear wall are designed to carry. Based on the material used, shear wall can be classified into the following types:

- Reinforced Concrete Shear Wall
- Concrete Block Shear Wall
- Steal Shear Wall
- Plywood Shear Wall
- Mid-Ply Shear Wall

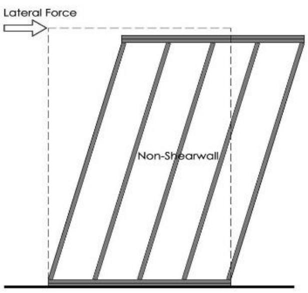


2. Problem statement:

As it’s mentioned earlier, shear walls structures are crucial for medium to high buildings. In fact, this kind of structural walls helps strengthen the entire structure during seismic or windy events. This simple solution prevents the collapse of the structure during the lateral forces experienced in a major earthquake. Normally, during an earthquake, the walls will move laterally, and if the seismic movement is great the structural connections can separate.



② SHEARWALL DIAGRAM



③ NON-SHEARWALL DIAGRAM

Nevertheless, the implementation such a structure can be high-priced. Hence, the main problem here is to optimize the cost of 3DReinforced Concrete (RC) Shear Wall structures while maintaining their good performance during seismic or windy events.

3. Solution:

A significant amount of research that has been performed in this area and aiming to find optimization methods for structural problems in three-folds: automating the complex process of design, optimizing the performance of the structure, or minimizing the total cost of the structure.

III. OPTIMIZATION ALGORITHMS:

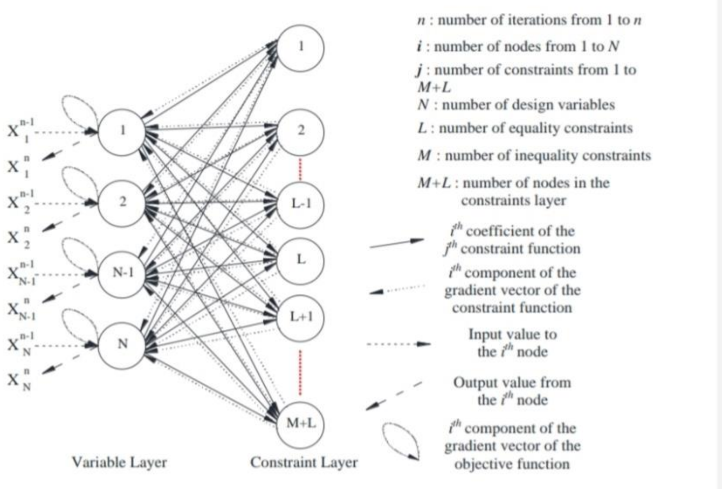
Civil engineering is defined as a discipline dealing with the design, construction, operation and maintenance of buildings and infrastructures such as bridges, roads, residences and towers. However, this industry is often considered as an industry with high energy consumption and a considerable environmental impacts while it demands a generous budget. Therefore, a significant amount of research has been performed in this area; with the development of computational methods for structure design and analysis, optimization methods based on mathematical programming techniques have been adopted in civil engineering in order to improve the social, environmental and economic performance of civil engineering projects.

These methods are solving problems in all different divisions of civil engineering. The problems can be structural, mechanical, hydraulic, transportation, geotechnical….

The general concept of these techniques is to select and find the best and optimal solution under specific conditions. Depending on the objective function, the solution required is either a maximum or a minimum value. The optimization techniques are usually based on mathematical programming using numeric search techniques. In this section, several structure optimization techniques are briefly described.

1) Neural Dynamic Model:

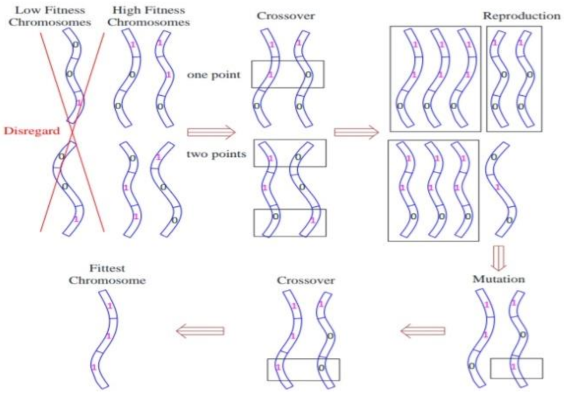
The Neural Dynamic Model is optimization method for large structural systems proposed by Adeli and Park. This model is based on the integration of a penalty function method, Lyapunov stability theorem, Kuhn-Tucker conditions and neural dynamic concepts. The problem here is modelled as a dynamic system with an equilibrium function where the optimum solution is the equilibrium point.


X_1^{n-1}
X_1^n
X_2^{n-1}
X_2^n
X_{N-1}^{n-1}
X_{N-1}^n
X_N^{n-1}
X_N^n
1
2
N-1
N
1
2
L-1
L
L+1
M+L
Variable Layer
Constraint Layer
n : number of iterations from 1 to n
i : number of nodes from 1 to N
j : number of constraints from 1 to $M+L$
N : number of design variables
L : number of equality constraints
M : number of inequality constraints
$M+L$: number of nodes in the constraints layer
i^{th} coefficient of the j^{th} constraint function
i^{th} component of the gradient vector of the constraint function
Input value to the i^{th} node
Output value from the i^{th} node
i^{th} component of the gradient vector of the objective function

2) Genetic Algorithm:

The Genetic Algorithm (GA) is based on the principle of genetics and natural law of survival of the fittest. After defining the objective function, the GA optimization process starts by creating a design population by converting the real design parameters into binary strings using binary coding. Next, the basic

GA operations of crossover, reproduction and mutation are performed on this population. The objective function value for each string is a survival potential indicator named fitness, a higher fitness value increases the chance for the string to be selected for mating and reproduction. Each chromosome or string in the GA solution space is independent of the others, hence, the search method in GA is a multi-path search, which searches many peaks in parallel. This helps reduce the possibility of entrapment in a local minimum. GAs have been used extensively for a variety of optimization problems such as design of long span suspension bridges, system identification, antenna design, and three-dimensional visualization and image analysis.

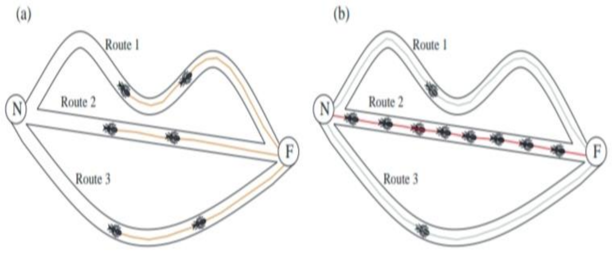


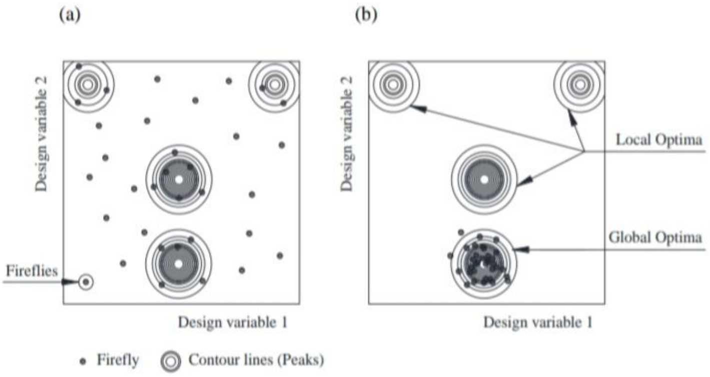
3) Practical Swarm Optimization:

Particle Swarm Optimization (PSO) principle is based on the movement of organisms such as in a bird flock or a school of fish when they travel to a certain destination. Each bird considers a certain direction to fly into. Then, all the birds communicate together to locate the bird with the best direction and speed toward that bird. Next, they start to investigate all possible flying directions from their new location. The process continues until the flock reaches its destination. PSO is initialized by creating a population (swarm) of candidate solutions (particles). The fitness value is evaluated for each solution i, and the best global solution in the current jth iteration/generation is considered, Xjg. For the next generation, a new value for candidate solution xij is computed based on $xi,j+1= xij+ vi,j+1$, where $vi,j+1$ is called the velocity which is updated for each solution in each generation using $vi,j+1=\omega vij + \alpha 1(Xil- xi) + \alpha 2 (Xjg- xi)$ in which Xil is the most successful value in the iteration history of the particle xi. The term ω is an inertia parameter which depends on the iteration number. Parameters $\alpha 1$ and $\alpha 2$ chosen within the interval (0,1) control the attraction of the current solution towards the best local and global solutions, respectively. PSO searches for the global optimum by using personal (local) experience and flock (global) experience of the particles, where each particle remembers its previously better visited solution, and considers the global best solution in each generation

4) Firefly Algorithm:

Firefly Algorithm (FA) design space has a population of solutions (fireflies). Every firefly (FF) flashes a light, the brightness of the light (equivalent to fitness function in GA) is proportional to the solution quality. In nature, FFs are unisex, so any FF can be attracted to any other FF. In the algorithm, FFs move toward the brighter ones for the purpose of mating by flying from one solution (firefly) to another to be closer to the optimum solution (the brightest/most attractive firefly). This is repeated until all the fireflies are attracted to the optimum solution.





5) Ant Colony Optimization:

Ant Colony Optimization (ACO) is inspired by ants’ behaviour when seeking for food. It is an iterative process where initial multiple solution paths are incrementally created by a population of agents (ants) moving in the design space. Ants have a dynamic memory to store information on the quality of previously visited paths. Ants leave a chemical trail behind them (pheromone) on their journey in each path. Ants can smell the pheromones, and choose the path with the strongest pheromone concentration. Shorter paths get marched over more frequently, hence, the pheromone trail becomes stronger on such paths and more ants are attracted to this path. The pheromone trail value for the paths is updated after each ant’s journey, so the more desired paths accumulate more pheromones, and less desired paths’ pheromones evaporate simultaneously

6) Stimulated Annealing:

In mechanics of materials, the physical annealing process is heating of the material until it turns into liquid, and all of the material particles are arranged randomly. Then, the temperature is lowered slowly and the material gains back its solid state with the particles arranged in a highly structured pattern. This fixes any defects with the original particles pattern, hence leaves the system with minimum free energy. The objective function in the Simulated Annealing (SA) optimization process corresponds to the energy function in the physical annealing process, the goal for both the objective function and the energy function is to search for the minimum.

7) Comparison of Algorithms

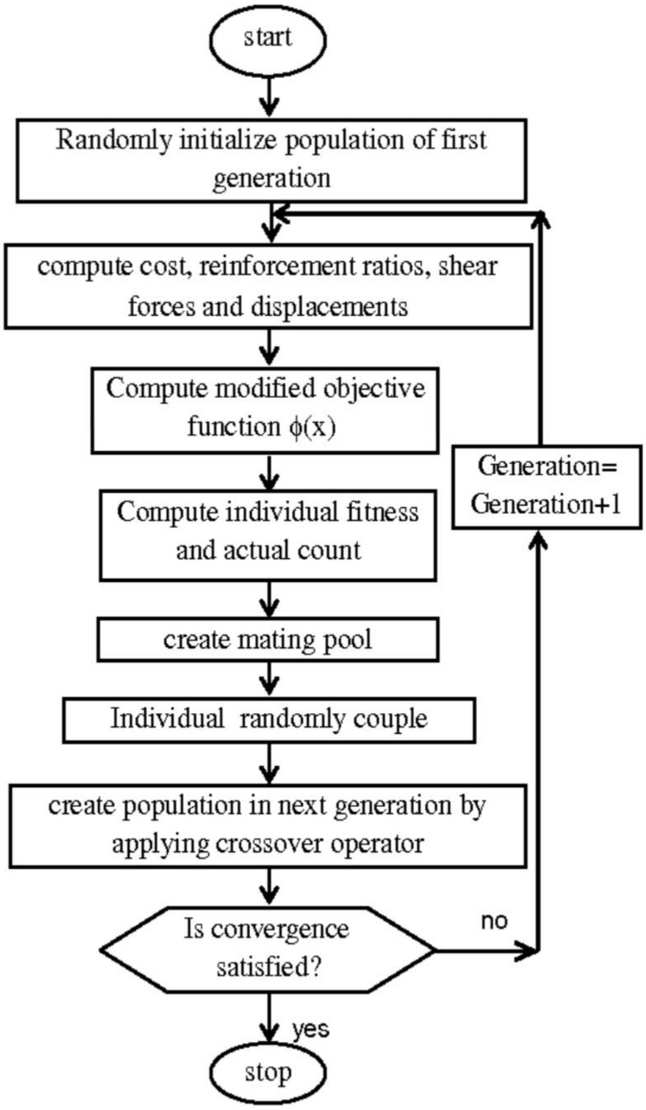
FA and PSO are similar in the way each individual location is updated through the attraction to a more fit individual in each iteration. While this updating method results in fast convergence, it also has a higher probability of being trapped in a local minimum compared with ACO, which is a more complicated and time-consuming technique. ACO avoids being trapped in a local optimum through the pheromone evaporation practice, which makes unwanted solutions less desirable in each iteration.

IV. APPLICATION OF OPTIMIZATION FOR RC SHEAR-WALLS STUCTURES:

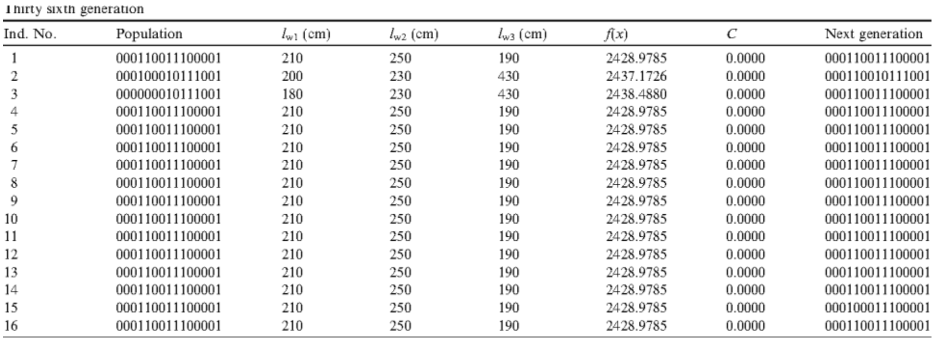
Reinforced concrete shear walls are widely used in many tall, super-tall and high-rise buildings for its excellent seismic behaviour. Seismic design of these structures, however, leading expensive structure. Therefore, structural optimization is required to minimize the total cost of the structure considering design criteria. The objective of the structural optimization is to design the structure in such a way to minimize the total cost of the structure by obtaining optimal cross-sections such as beam, column and shear wall. Here, cost of the structure refers to weight or material consumption of the structure.

1. Cost optimization via genetic algorithm:

- Flowchart for cost optimization by genetic algorithm


start
Randomly initialize population of first generation
compute cost, reinforcement ratios, shear forces and displacements
Compute modified objective function ϕ(x)
Compute individual fitness and actual count
create mating pool
Individual randomly couple
create population in next generation by applying crossover operator
Is convergence satisfied?
no
Generation= Generation+1
yes
stop

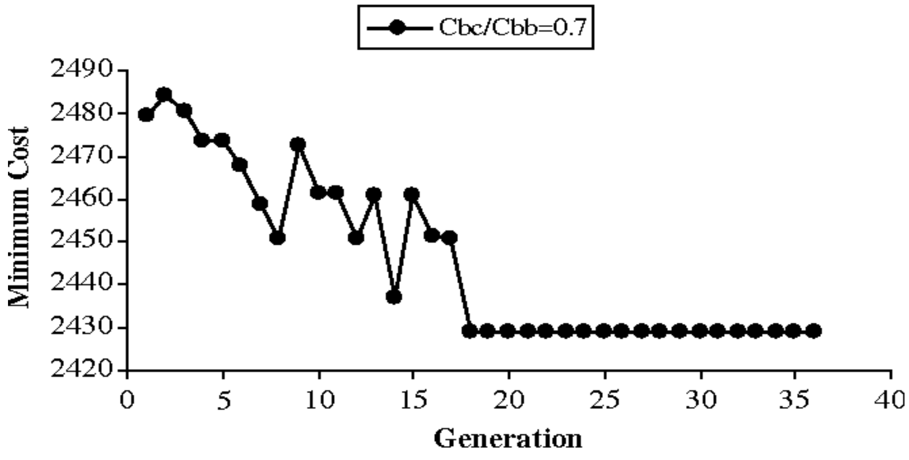
- ➢ Thirty sixth generation



Thirty sixth generation

Ind. No.	Population	l_{w1} (cm)	l_{w2} (cm)	l_{w3} (cm)	$f(x)$	C	Next generation
1	000110011100001	210	250	190	2428.9785	0.0000	000110011100001
2	000100010111001	200	230	430	2437.1726	0.0000	000110010111001
3	000000010111001	180	230	430	2438.4880	0.0000	000110011100001
4	000110011100001	210	250	190	2428.9785	0.0000	000110011100001
5	000110011100001	210	250	190	2428.9785	0.0000	000110011100001
6	000110011100001	210	250	190	2428.9785	0.0000	000110011100001
7	000110011100001	210	250	190	2428.9785	0.0000	000110011100001
8	000110011100001	210	250	190	2428.9785	0.0000	000110011100001
9	000110011100001	210	250	190	2428.9785	0.0000	000110011100001
10	000110011100001	210	250	190	2428.9785	0.0000	000110011100001
11	000110011100001	210	250	190	2428.9785	0.0000	000110011100001
12	000110011100001	210	250	190	2428.9785	0.0000	000110011100001
13	000110011100001	210	250	190	2428.9785	0.0000	000110011100001
14	000110011100001	210	250	190	2428.9785	0.0000	000110011100001
15	000110011100001	210	250	190	2428.9785	0.0000	000100011100001
16	000110011100001	210	250	190	2428.9785	0.0000	000110011100001

- ➢ Generation minimum cost:



➡ In this optimization problem the shear wall dimension has been considered as a design variables and it has been aimed at searching the optimum shear wall dimensions that minimize the total material cost.

2. Formulation of the cost optimization method:

The optimization problem is defined as follows:

Find X= $(b_b, d_b\ , b_c, d_c\ \ , t_w, L_w)$ to minimize F(X) = $C_cV_c + C_sV_s$ subjected to g(X)≤ 0

- Design variables:
  X indicates section sizes of:
  - ➢ Beams: $b_b\ d_b$

  - Columns : b_c $d_{c,}$
  - Walls: t_w L_w
- Objective function:
  Many objectives functions can be used to define the optimum solution. In this problem, the objective function to be minimize is the total cost of reinforcement concrete considering the difference of the cost of the concrete and steel bar.
  $V_c = \sum_{i=1}^{N} V_{cbi} + \sum_{i=1}^{N} V_{cci} + \sum_{i=1}^{N} V_{cwi}$
  $V_s = \sum_{i=1}^{N} V_{sbi} + \sum_{i=1}^{N} V_{sci} + \sum_{i=1}^{N} V_{swi}$

  $where\ C_c and\ C_s$are giving.

- Constraint functions:
  Only formulations related to the upper bound of reinforcement ratio and story drift are considered. As for the section sizes both upper and lower limits are applied. In other words, g(X) presents the stresses in the members.
  g(X) = R(X)- R_{min} (X))≤ 0
  g (X) = $R_{max}(X)$ -R(X))≤ 0

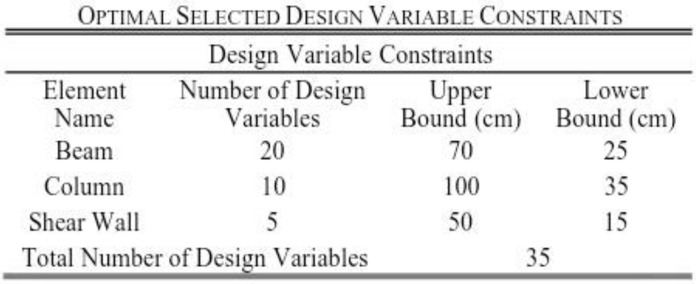
3. Example:

a. Optimization Problem:

Let's consider a 15 storied shear wall-frame structure with 3 pans with length of 9m, 7.5m and 7m in each horizontal direction, and with typical height of 3m respectively. Beams have rectangular and columns have square shape. Walls are placed between beams. The section sizes of beams and columns, and the thickness of walls are design variable.

For the wall, lengths are fix to 300 cm. The section sizes for the shear walls are predetermined as 5 sizes for every three stories.

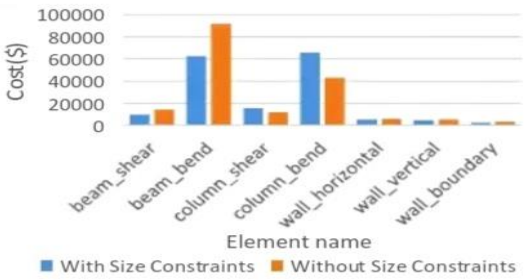
The assumed dead and live loads on slabs for each floor are 7.5 KN/m2 and 5.5KN/m2 respectively. The assumed dead load on each frame of the floors is 12.5 KN/m. The compressive strength of Concrete is 27 MPa and yield strength for reinforcement is 420 MPa for all section sizes.



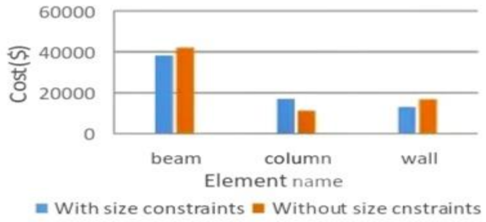
OPTIMAL SELECTED DESIGN VARIABLE CONSTRAINTS

Design Variable Constraints			
Element Name	Number of Design Variables	Upper Bound (cm)	Lower Bound (cm)
Beam	20	70	25
Column	10	100	35
Shear Wall	5	50	15
Total Number of Design Variables		35	

b. Optimization Results:

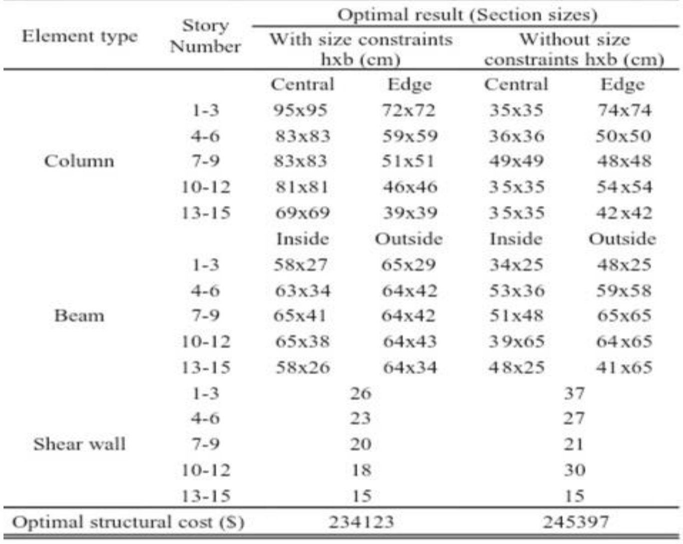


Cost ratio of steel bar of each element



Cost ratio of concrete of each element

OPTIMAL SELECTED DESIGN VARIABLE CONSTRAINTS



Element type	Story Number	Optimal result (Section sizes) With size constraints hxb (cm)		Without size constraints hxb (cm)	
		Central	Edge	Central	Edge
Column	1-3	95x95	72x72	35x35	74x74
	4-6	83x83	59x59	36x36	50x50
	7-9	83x83	51x51	49x49	48x48
	10-12	81x81	46x46	35x35	54x54
	13-15	69x69	39x39	35x35	42x42
		Inside	Outside	Inside	Outside
Beam	1-3	58x27	65x29	34x25	48x25
	4-6	63x34	64x42	53x36	59x58
	7-9	65x41	64x42	51x48	65x65
	10-12	65x38	64x43	39x65	64x65
	13-15	58x26	64x34	48x25	41x65
Shear wall	1-3	26		37	
	4-6	23		27	
	7-9	20		21	
	10-12	18		30	
	13-15	15		15	
Optimal structural cost ($)		234123		245397	

The optimal result includes practical section sizes, minimum total cost of the structure considering cost of concrete and steel bar for beams, column and shear wall.

From the results, it can be understood that it is important to respect size constraints because it is more practical (larger column, smaller beam and walls) and it has 4.6% lower cost than the solution without size constraint.

As a conclusion, this problem had multimodal solution space and strong dependency on initial sectional sizes. In this case, the size constraint is crucial in finding practical and effective sectional size with lower cost.

V. APPLICATION IN MOROCCO:

The Optimization method described above is a quite simple and useful methods that, in my opinion, can be applicable in Morocco. Within the framework of the program “Rabat, Ville Lumière, Capitale Marocaine de la culture”, the Moroccan government is working on high quality construction projects that can compete with international outstanding structures. BESIX and Travaux Generaux de Construction de Casablanca are building the Mohammed VI tower, the tallest tower in Africa. The 205 metres tower has 55 floors with a luxury hotel, offices and apartments. The building can withstand not only the usual element, such as winds and seismic event but also flooding from the Bouregreg river. In this case, the application of the method would be an optimal and an effective solution for a such exceptional building and with a lower budget.

VI. SUMMARY AND CONCLUSIONS:

To summarize, the sizes constraint has a crucial role in a cost optimization problem to obtain practical section sizes and then build a seism and wind resistant structure with a lower cost

It seems to me that the cost optimization of RC Shear Wall structure is not representing only an economic solution of minimizing the budget. But also an environmental solution, that’s because it’s based on minimizing the section sizes of the structures. That means using less materials and then having less construction waste.

VII. REFERENCES:

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